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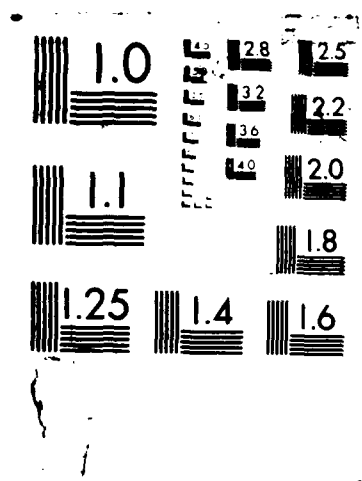
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NONLINEAR SURFACE POLARITONS

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<p>Analytical and numerical (the Beam Propagation Method) techniques were used to analyze a variety of nonlinear optics phenomena at surfaces and in thin-film waveguides. A number of new device possibilities for all-optical signal processing were identified.</p> <p>New nonlinear guided-wave phenomena have been predicted, of which many are of interest for potential experimental and device applications. The highlights are:</p> <ul style="list-style-type: none"> (1) The analytical solutions for highly nonlinear waves guided by single interfaces and thin films extended to realistic media which exhibit saturation in the optically induced index change. (2) Beam propagation techniques used to find the stability of nonlinear guided waves for the first time. Furthermore, non-stationary nonlinear guided waves were found, also for the first time. (3) The generation of solitons predicted for nonlinear waveguides excited at high powers. Applications to optical limiters and optical logic via the exchange of solitons identified. The effects of non-ideal excitation conditions, waveguide absorption, and index saturation investigated. (4) Analytical and numerical solutions for nonlinear TM-polarized guided waves obtained for the first time. (5) The feasibility of light-by-light modulation using nonlinear guided waves of both polarizations predicted. (6) The origin of bistability in nonlinear prism couplers fully explained for the first time. (7) The response of nonlinear directional couplers to very high excitation calculated, resulting in unexpected steady-state conditions. 					
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INTRODUCTION

In the last few decades, nonlinear optics has taken a central role in many applications based on four-wave mixing and an intensity-dependent refractive index. Two of the most intriguing questions posed in the last few years are: 1) what role, if any, solitons will play in optics, and 2) whether sub-picosecond all-optical signal processing based on guided waves will be possible. Solutions to the nonlinear wave equation for media containing Kerr-law nonlinearities were known for a number of years prior to the start of this program. However, only recently, with this research program playing a leading role, have numerical investigations revealed the full richness of the phenomena involved. Power-dependent waves guided by the interface between two media (at least one of which has a self-focusing nonlinearity; i.e., index increases with power) were studied initially. It was soon realized however, that a thin film bounded by media of lower index (at low guided-wave powers) is the optimum geometry, since it also supports guided waves at low powers, commonly known as integrated-optics waveguides. Waveguides are ideal for efficient nonlinear interactions because they confine light to beam cross-sections on the order of the wavelength of light. Consequently, much of our work has concentrated on thin-film waveguides.

Three years ago this program to investigate nonlinear surface polariton phenomena was begun, in collaboration with A. A. Maradudin and R. F. Wallis at the University of California at Irvine. In the last eighteen months, most specifically with the arrival of E. M. Wright (recently promoted to Research Assistant Professor), an independent theory program has been developed at the University of Arizona. Simultaneously, both the fundamental and device-related aspects of nonlinear guided-wave interactions were under experimental investigation.

REVIEW OF ACCOMPLISHMENTS

Background

The theoretical program has led to a number of significant advances in the understanding of nonlinear guided-wave phenomena and has identified a number of potential applications to all-optical devices. The results have been reported in a series of publications,¹⁻³¹ and led to a number of invited papers³²⁻⁵² concerning both experiment and theory.

The geometry examined most frequently consists of a thin film (of refractive index n_f) bounded by a nonlinear cladding ($n = n_c + n_{2c}S$) and/or a nonlinear substrate ($n = n_s + n_{2s}S$), where S is the local intensity. For TE waves polarized in the y direction, Maxwell's equations lead to the following mixed linear-nonlinear Schrodinger equation governing the evolution of the complex electric field:

$$\frac{\partial^2 E}{\partial x^2} + 2i\beta k \frac{\partial E}{\partial z} - k^2 [\beta^2 - n^2(x,S)] E = 0 .$$

Here z and x are the propagation and transverse coordinates, and β is an appropriate background effective index. This equation admits nonlinear guided-wave solutions of the form

$$E(x,z) = E_g(x, P_{gw}) e^{ik\beta(P_{gw}) z} ,$$

where, in general, both the guided-wave effective index and the field profile depend on the guided-wave power, P_{gw} . It is usually the variation in β and $E_g(x)$ with guided-wave power which leads to unusual and potentially useful properties of the guided waves. This program has primarily used two approaches to solve these equations for a variety of multilayer geometries. Steady-state solutions are obtained when $\partial E / \partial z = 0$. Beam propagation methods are particularly valuable for investigating cases where $\partial E / \partial z \neq 0$.

Results

The following phenomena, based on steady-state solutions to the nonlinear wave equation, have been demonstrated theoretically. Ideal Kerr-law nonlinearities in the media bounding the film were assumed.

- (1) For self-focusing media and under well-defined conditions, there is a threshold power above which guiding occurs. This leads to an all-optical lower threshold device.^{1-5,15,16,20}
- (2) For self-defocusing media, there is an upper limit to the power guided. This is essentially an optical limiter.^{1-5,15,16,20}
The combination of these two effects could lead to an all-optical Schmitt trigger, a key component in any all-optical system.
- (3) Saturation effects have been included in the steady-state solutions and the effect on various nonlinear guided waves clarified. In particular, it was shown that a

value for the saturation index which is too small eliminates thresholding action for (1) and (2) above.^{6,7,12,13,15,16,20}

This result identifies a material limitation on the operation of all-optical devices.

In addition, numerical beam propagation methods (BPM) have been developed in collaboration with J. V. Moloney of Heriot-Watt University and the following results obtained.

- (4) Not all of the nonlinear guided-wave branches for self-focusing bounding media are stable. Unstable solutions emit spatial solitons into the bounding media as they evolve into stable solutions.^{10,13,16,20}
- (5) Nonstationary, stable solutions to the nonlinear wave equation in which the field distributions remain guided and oscillate with distance were discovered.^{11,13,16,18-20}
- (6) Stable waves can be excited by focusing appropriately tailored Gaussian beams onto the endface of a nonlinear waveguide. If the power is too high, the excess power leaves the film region by means of successive emission of solitons, thus limiting the power guided in the region of the film.^{18-21,24}
- (7) Absorption leads to interesting overshoot phenomena for soliton-like waves. In the limit of weak absorption, soliton propagation still occurs.²²
- (8) Until recently, all of the progress by this group and others in the field has been for TE-polarized waves. The TM case was generally believed to be intractable; however, analytical formulae for the TM dispersion curves have been obtained for the first time. Also, in collaboration with A. D. Boardman's group, purely numerical techniques were applied to the solution of the TM problem.^{17,25,26}
- (9) Solving the TM problem allowed consideration of weak-strong beam combinations for combination TE- and TM-polarized waves. It has been shown that 100% modulation of one beam by a weak modulation of the second beam is possible.^{27,28}
- (10) There is a long-standing controversy about whether bistability can be obtained when light is prism-coupled into a nonlinear waveguide. It was shown numerically that bistability can be obtained only with non-local nonlinearities, or with reflections at the prism end. Purely local nonlinearities lead only to switching.²⁹

This explains the observation of bistability for thermal nonlinearities in a number of experiments by this group and others.

- (11) One of the potentially most versatile all-optical guided-wave devices is the nonlinear directional coupler. The steady-state response of this device has been solved. A number of totally unexpected steady-state power distributions between the two channels were found.³¹

Conclusion

In terms of applications, the above results identify which branches of the new solutions can actually be used to propagate guided-wave power. The common occurrence of spatial solitons in these nonlinear systems begs the question of whether new device concepts based on the exchange of solitons are possible. Research is continuing in this area.

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